Correlation of the SAGE III on ISS Thermal Models to Test and Flight Data

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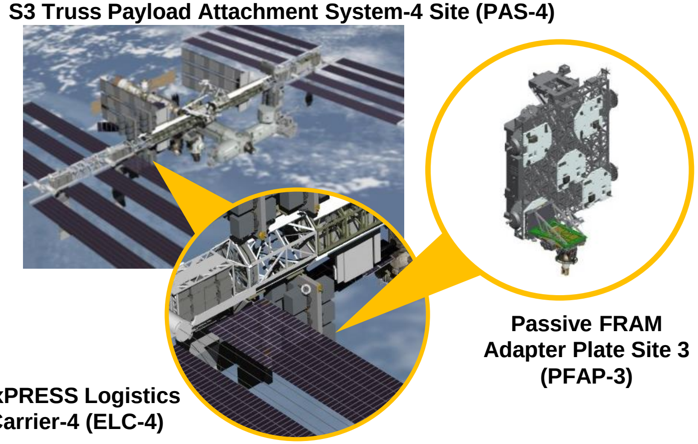
Agenda

- SAGE III on ISS background
- Approach to Thermal Vacuum (TVAC) Testing and Correlation
- TVAC Correlation Achievements and Lessons Learned
  - Interface Adapter Module TVAC
  - Instrument Assembly TVAC
  - Chamber Characterization
  - Instrument Payload TVAC
  - Summary of lessons learned
- Correlation to Flight Data
- Summary

SAGE III on ISS Background

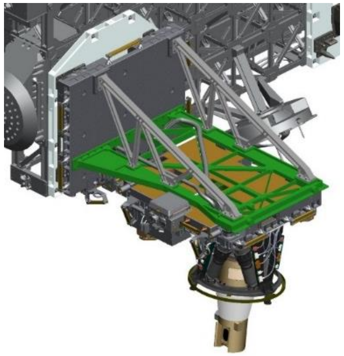
- Stratospheric Aerosol and Gas Experiment
- Fifth in a series of instruments developed to monitor ozone, aerosols, and other trace gases in Earth’s stratosphere and troposphere
- Partnership between NASA Langley Research Center (LaRC), Thales Alenia Space- Italy (TAS-I), and Ball Aerospace and Technologies Company (BATC)
- Launched to the International Space Station (ISS) via Space X Falcon 9 in February 2017
- Consists of two payloads – Instrument Payload (IP) and Nadir Viewing Platform (NVP)

S3 Truss Payload Attachment System-4 Site (PAS-4)



ExPRESS Logistics Carrier-4 (ELC-4)

Passive FRAM Adapter Plate Site 3 (PFAP-3)

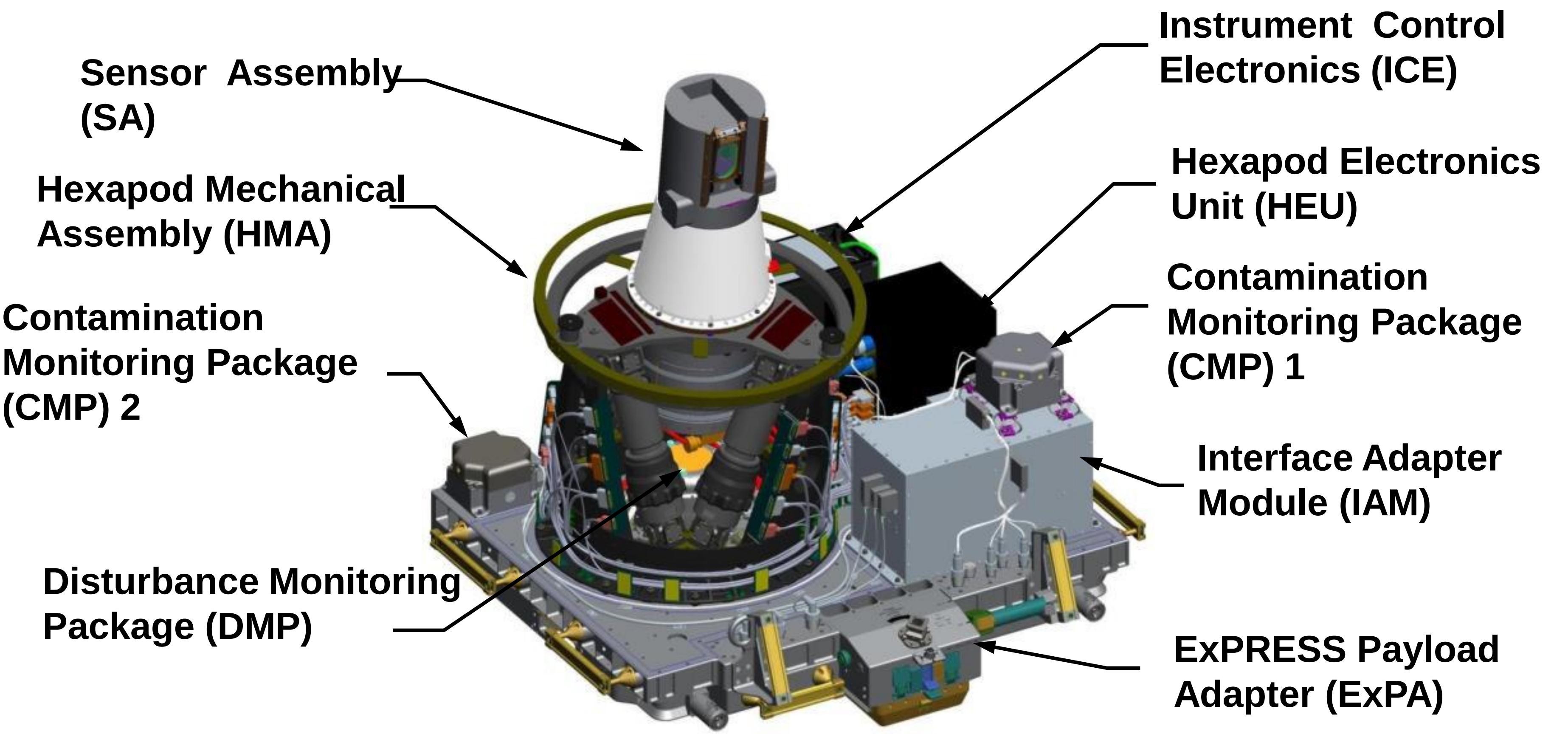


SAGE III On-Orbit Configuration

Payloads in Dragon Trunk (CRS-10)

SAGE III In-Transit to ELC-4

Instrument Payload (IP)



General TVAC Test Approach

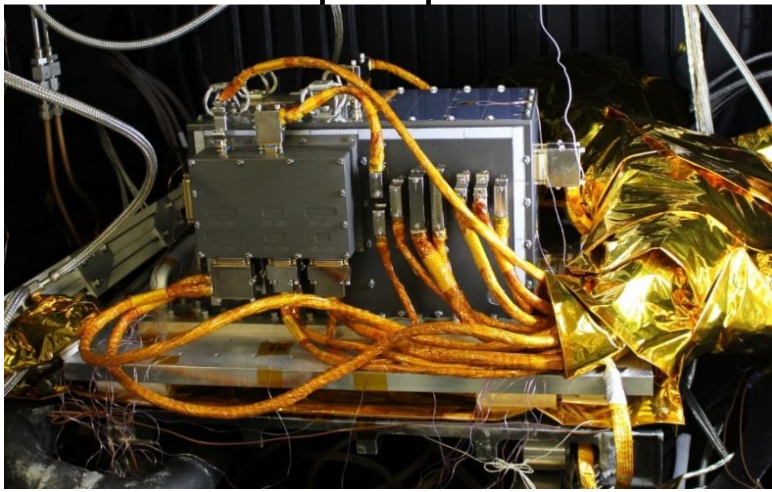
- All TVAC test scenarios modeled in Thermal Desktop® (TD) within system flight model
- Primary goals:
  - Evaluate behavior in vacuum at hot and cold conditions
  - Obtain data for model correlation
- Test profiles included these 5 thermal balances:
  - Unpowered hot & cold
  - Heater-only cold
  - Operational hot & cold
- Transient unpowered cool-down with constant environment included in test profile

General Correlation Approach

- Pre-test model predictions used as starting point
- Thermal model correlated to balances and transient power-on and power-off
  - Unpowered cases completed first; fewest variables
- Measurements included flight sensors, test TCs, and subsystem current draw
- Main adjustments made during correlation:
  - Contacts between parts
  - Optical properties
  - Component dissipated power
- Transient analysis performed for better accuracy
- Root-mean-square (RMS) errors calculated over entire timeline, all sensors
- Goal for model correlation: RMS error < 5°C

Interface Adapter Module (IAM) TVAC

- New build, flight computer and power distribution unit
- MLI on back, silver Teflon all other sides
- Operational and survival heaters controlled via mechanical thermostats
- Tightly-coupled to chamber interface plate in flight-like configuration using thermal epoxy
- Primary adjustments made in correlation:
  - Power dissipation
  - Conductors from boards to chassis, chassis to adapter plate



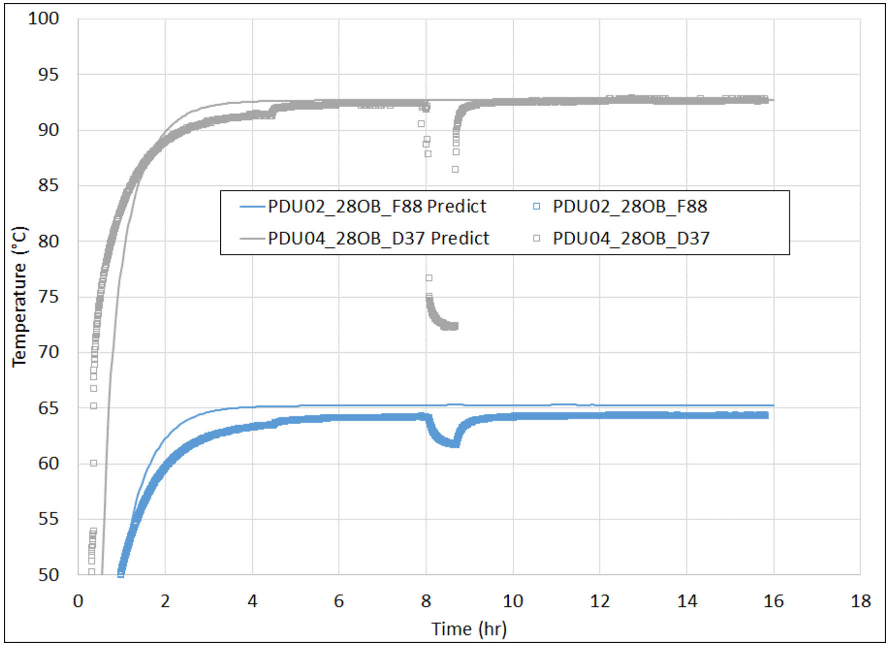
IAM Correlation Quality

- Overall RMS error is less than 2°C - indicates excellent correlation

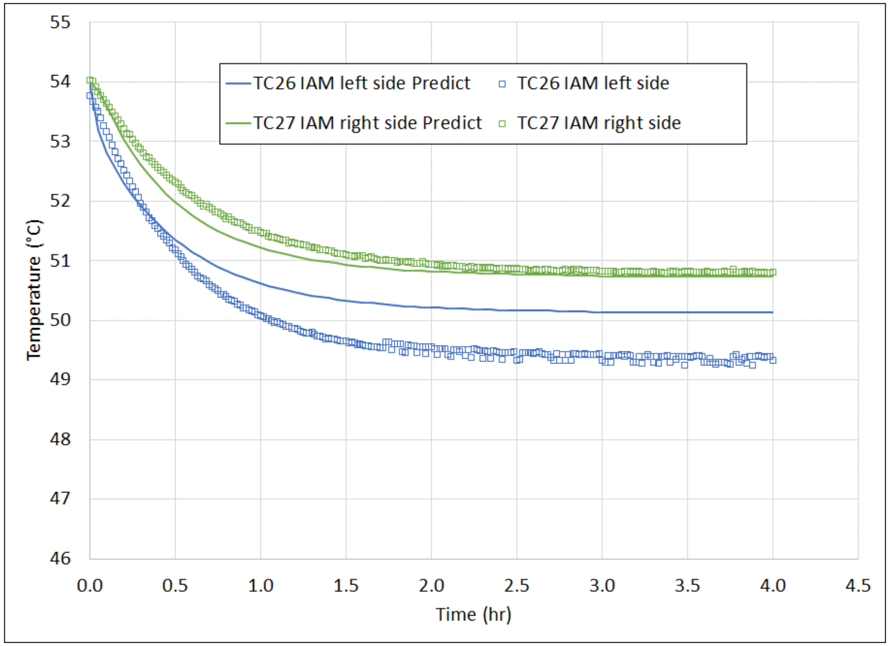
Steady-State Results	Hot Unpowered	Hot Powered	Cold Unpowered	Cold Powered	Overall RMS
Overall RMS error (°C)	1.7	1.1	1.0	3.1	**1.9**
Flight sensor RMS error (°C)	0.9	1.1	0.7	3.7	**2.0**
Avg error (°C)	0.4	0.4	-0.7	-1.5	**-0.4**

Transient Results	Hot Cooldown
Overall RMS error (°C)	1.1
Flight sensor RMS error (°C)	**1.2**
Avg error (°C)	0.1

IAM Correlation Plots



Hot Powered Steady-State



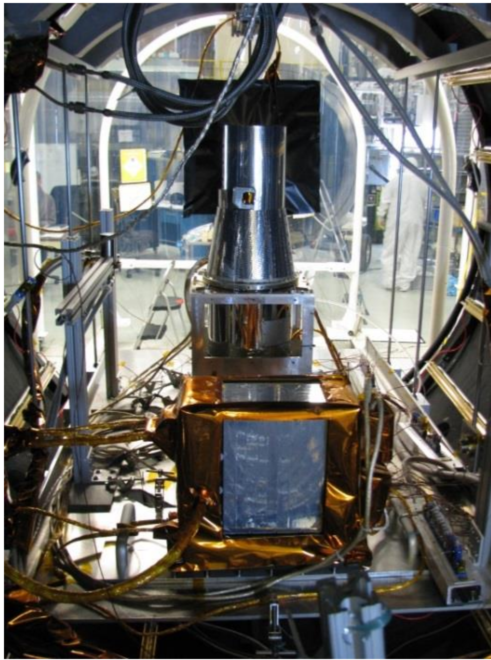
4-hr Cool-Down Transient

IAM TVAC Correlation Lessons Learned

- Test TCs should be attached with high-conductivity tape to minimize error if TC bead lifts off surface
- Mock payload interfaces should be as flight-like as possible for subsystem-level TVAC
  - Surface characteristics (roughness, finish, etc.)
  - Fastener torque specifications
  - More temperature sensors typically available to characterize interface

Instrument Assembly (IA) TVAC

- Consists of the Sensor Assembly (SA) and Instrument Control Electronics (ICE)
  - Hardware built in late 1990’s
- IA contains heaters, rotating azimuth motor, rotating scan mirror, thermo-electric cooler (TEC)
- Exterior surfaces mainly silver-Teflon
- Conductive interfaces designed to be flight-like
- Quartz lamps used for heating (6 zones)
- Primary adjustment made in correlation
  - Contact between parts



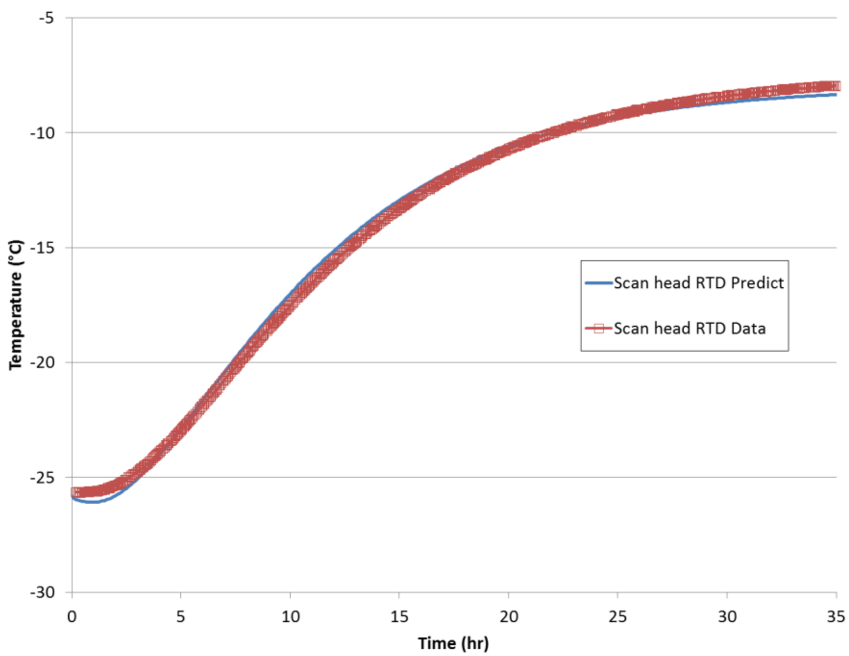
IA Correlation Quality

- Overall RMS error for flight sensors less than 1.5°C - indicates excellent correlation
- Main adjustments were to contacts

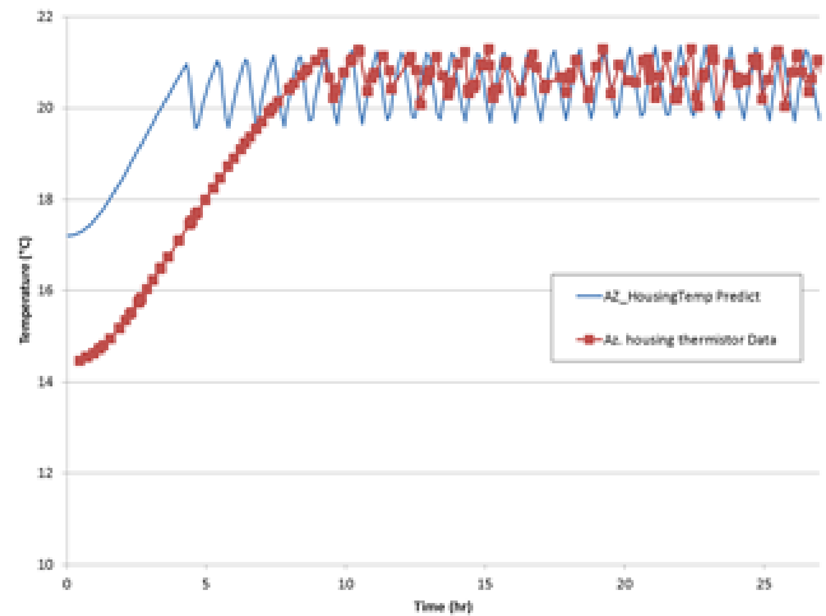
Balance Results	Hot Unpowered	Hot Powered	Cold Unpowered	Cold Heater-only	Cold Powered	Overall Average
Overall RMS error (°C)	1.5	1.7	1.3	2.8	3.9	**2.4**
Flight sensor RMS error (°C)	0.6	2.2	0.5	1	1.8	**1.4**
Avg error (°C)	0.0	-0.6	0.3	1.1	0.6	**0.3**

Transient Results	Hot Powerup	Hot Cooldown	Cold Powerup	Cold Heater Powerup	Cold Cooldown	Overall Average
Overall RMS error (°C)	1.4	0.4	2.4	2.8	1.0	**2.0**
Flight sensor RMS error (°C)	1.4	0.6	1.2	1.7	0.9	**1.3**
Avg error (°C)	-0.1	0.1	1.3	0.8	-0.7	**0.3**

IA Correlation Plots



Cold power-on transient



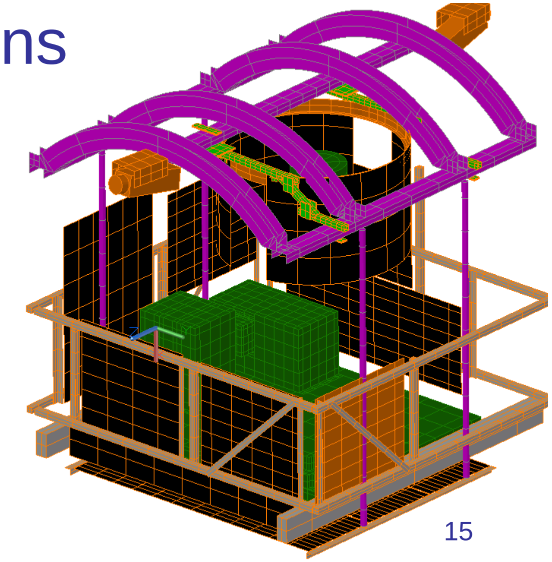
Azimuth heater operation

IA TVAC Correlation Lessons Learned

- Correlation of heater operation to heater-only balance worked well
- Unpowered cool-downs helpful in thermal mass correlation
- Transient cases provide more accurate prediction of behavior, even for quasi-steady-state
- Correlation of TEC behavior
  - Required modification of TEC parameters due to degradation
  - Test data when TEC data went out of the control range valuable
- Chamber shroud had larger gradients than expected, should be well-instrumented
- Issues with quartz lamps led to facility characterization test to perform IA model correlation
  - Fraction of infrared (IR) vs. solar
  - No power measurement

TVAC Chamber Characterization

- Heater plate system designed for payload-level test
  - Avoids quartz lamps
  - Allows for independent control of subsystems
- Test to characterize heater plate system
  - Verify capability to achieve target temperatures
  - Determine heater plate gradients
  - Correlate thermal model of chamber
- Test paused to remove MLI from two plates to achieve goal temperatures; repeated test conditions
- Primary correlation adjustments:
  - MLI
  - Plate emissivity
  - Contact between plates and frame
  - Mesh on plates



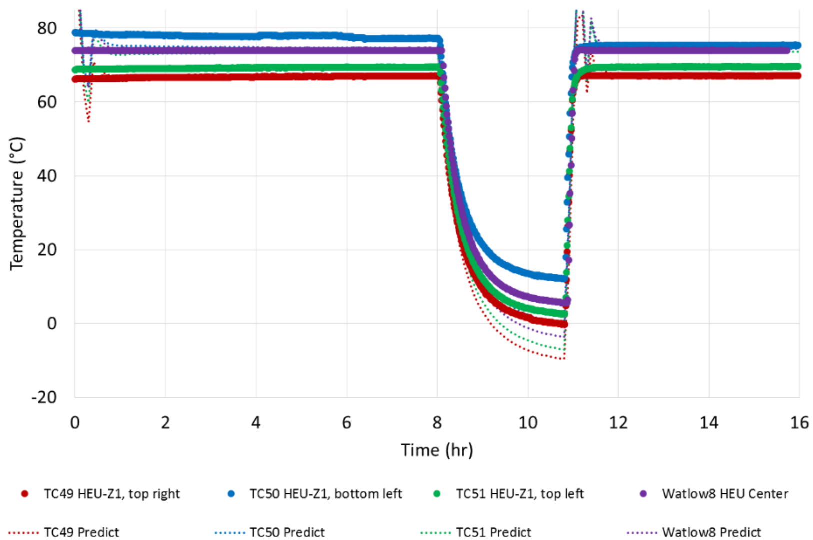
Characterization Correlation Quality

- Overall RMS error for final configuration below 5°C - indicates good correlation
  - Errors higher in original configuration due to using standard TD modeling method for MLI covering surfaces at different temperatures
  - Slight tendency toward over-prediction
- Model accurately tracked response of neighboring plates to heater power changes - gives a high level of confidence in the model

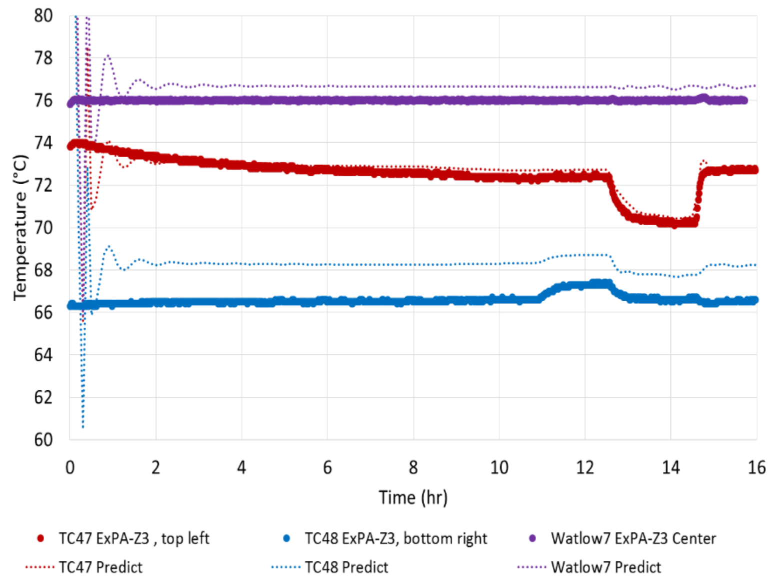
		Hot Survival	Hot Op	Cold Survival	Hot Op 2	Cold Survival 2	Overall Average
Errors on mock payload and ExPA (°C)	RMS error	4.8	4.7	5.8	1.9	3.8	**4.2**
	Average error	4.5	0.7	-1	-1.5	3.1	**1.2**
Errors on heater plates and frame (°C)	RMS error	3.4	3.4	3.9	2.9	3	**3.3**
	Average error	2.1	0.9	-1.5	1.4	1.4	**0.9**

Configuration Change

Characterization Correlation Plots



Heater plate cooldown correlation



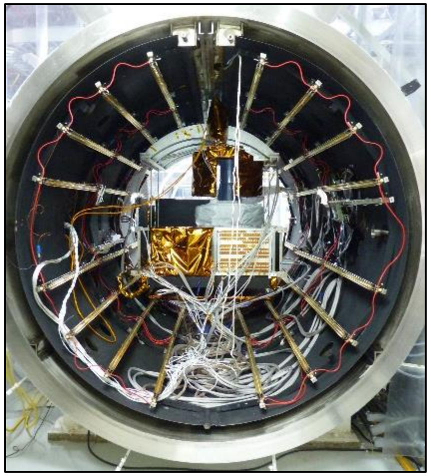
Neighboring plate reaction to cooldowns

Characterization Lessons Learned

- For MLI covering multiple plates at different temperatures, cannot use Insulation tab on TD surface
  - Insulation must be modeled explicitly to get correct radiative transfer under MLI
- Place temperature sensors to verify basic assumptions, such as thermal contact between parts
- Chamber emissivity lower than assumed at cold conditions
- Plate gradients ~10°C despite even distribution of heaters across aluminum plates
  - Well-predicted following correlation

Instrument Payload (IP) TVAC

- Flight IP and custom heater plate system
- IP contains operational and survival heaters, multi-layer insulation (MLI), silver Teflon, and TECs
- Included orbit simulations for correlation to a flight-like transient motor power profile
- Primary adjustments made in correlation:
  - Contact between trolley and chamber
  - Emissivity
  - MLI effective emissivity
  - Conductance to the ExPA and between parts

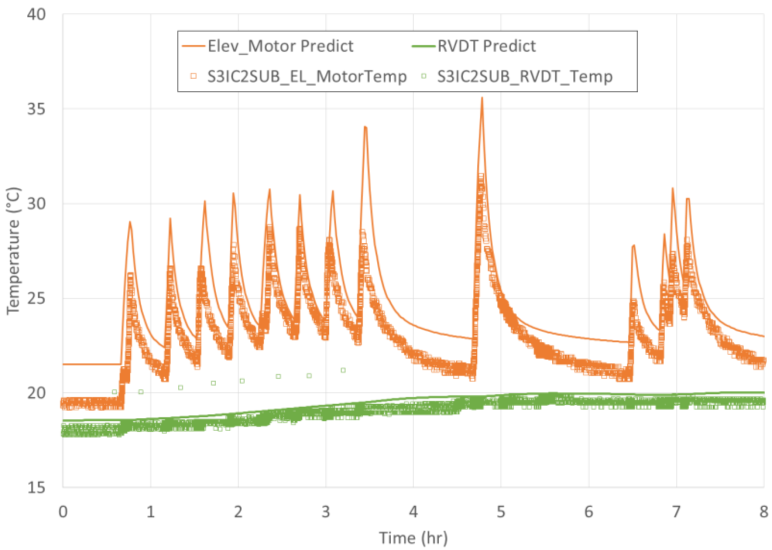


Overall IP Correlation Quality

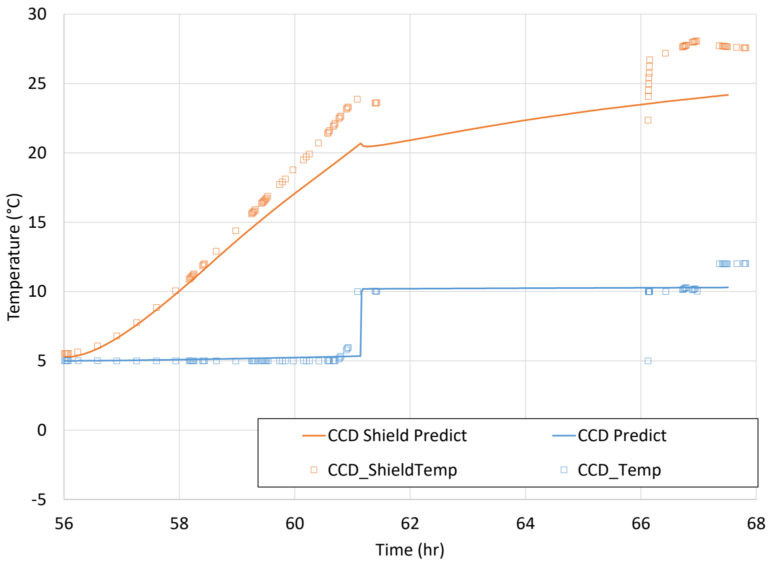
- Facility thermocouple data not included in RMS error calculations due to excessive noise
- Overall RMS error is less than 2.5°C - indicates remarkable correlation for a complex model
  - Slight tendency toward under-prediction

	Hot Unpowered	Cold Unpowered	Hot Powered	Cold Powered	Hot Cooldown	Cold Cooldown	Overall average
RMS error for flight sensors (°C)	1.1	2.7	1.7	2.8	3.2	2.6	**2.4**
Avg error for flight sensors (°C)	-0.9	-0.1	0.1	0.8	-2.3	-1.2	**-0.6**

IP Correlation Plots

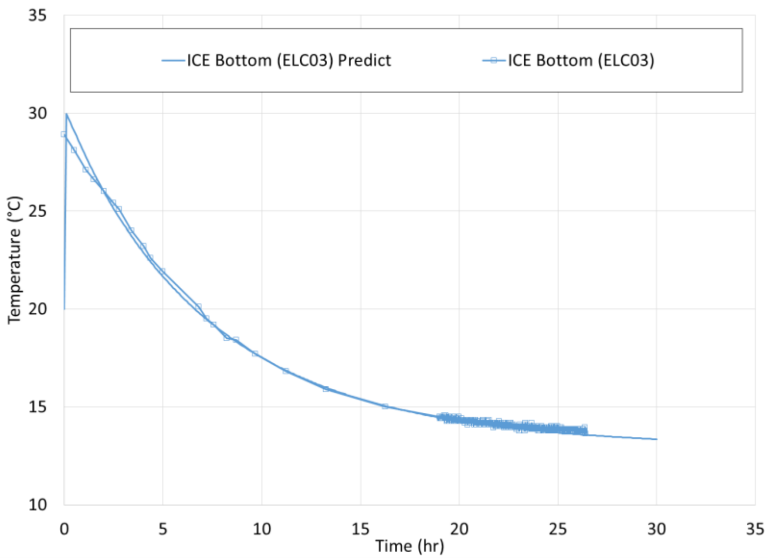


Correlation to operation of elevation motor during science events

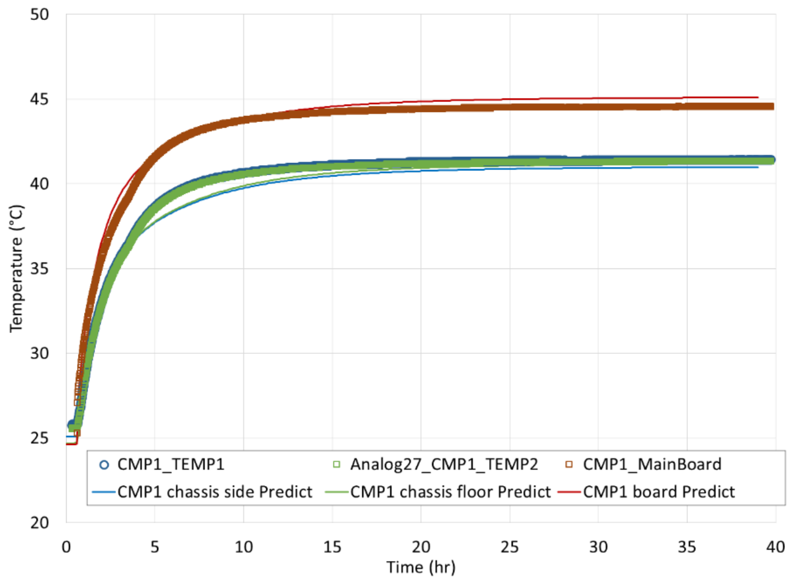


Correlation to operation of heater and TEC

IP Correlation Plots



Hot unpowered transient correlation



Hot powerup transient correlation

IP Correlation Lessons Learned

- High noise observed in test TCs due to wire routing – check prior to test start
- Balance sequence effective for correlation
  - Unpowered correlation first, quasi-steady-state and then transient
  - Transient for heater power-up
  - Transient to powered operation
  - Powered balance
  - Power-off for cooldown transient
- Accurate power calculations required measured current and resistance
- Run time reduced via modification of TEC power dissipation equation

Flight Correlation

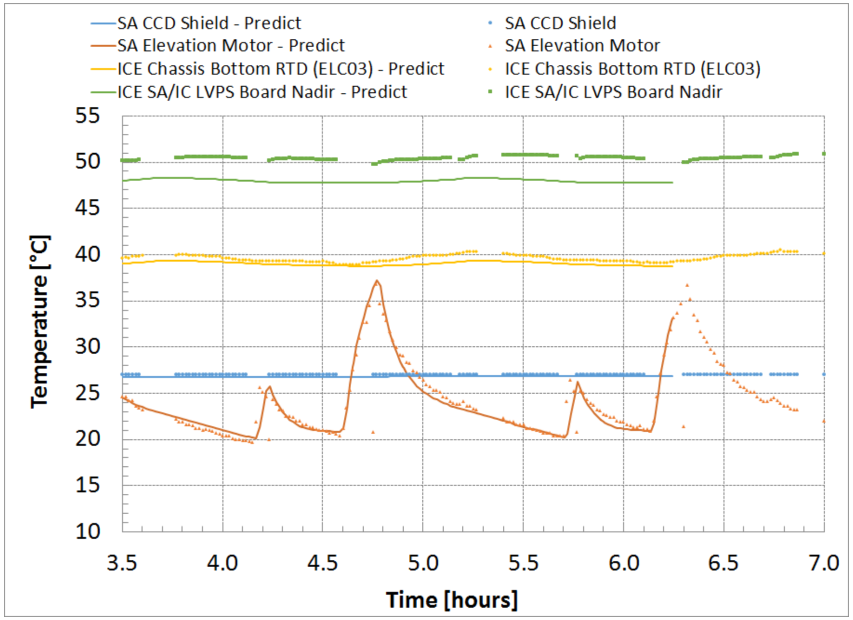
- SAGE III launched on SpaceX CRS-10 mission in February
- Operational on ELC-4 since March 10th
- Beta angle range experienced to-date between -38° and +73°
- Primary areas of focus:
  - Worst-case beta angles for hot operations
  - Elevation motor temperature during science events
  - ExPA temperature at high-negative beta
- Major model adjustments:
  - Power
  - Optical properties
  - Conductors between internal instrument parts

Flight Correlation Quality

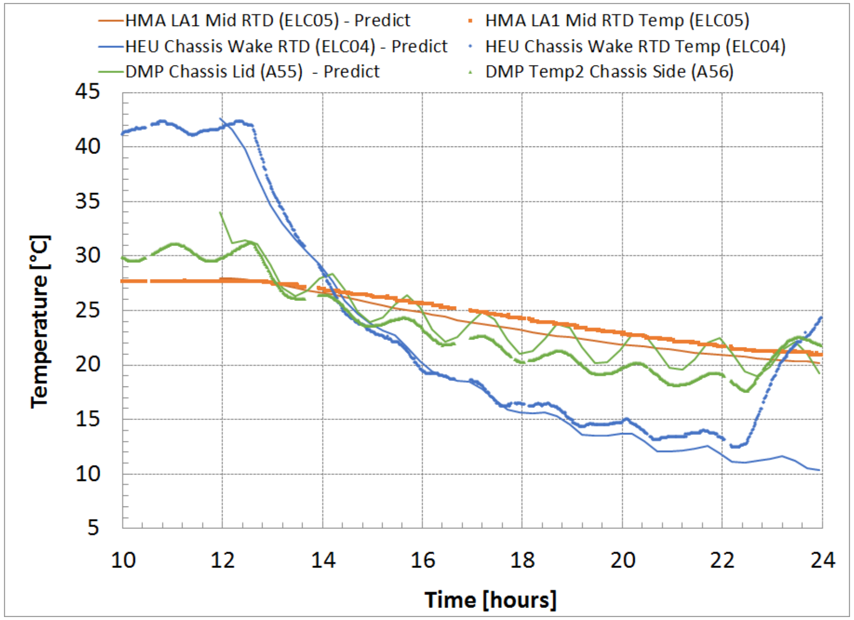
- Beta 41° worst-case hot case for most components
  - Good matching; overall RMS error is < 3°C
- Beta -38° worst-case hot case for SA (to-date)
  - Good matching for SA
  - ExPA-coupled components under-predicting by up to 12°C

	β = 73°	β = 50°	β = 41°	β = -24°	β = -38°	Overall
RMS error for flight sensors (°C)	8.4	3.9	**2.6**	3.7	4.3	**4.6**
Avg error for flight sensors (°C)	8.0	3.1	-0.3	-2.7	-3.4	1.0

Flight Correlation Plots



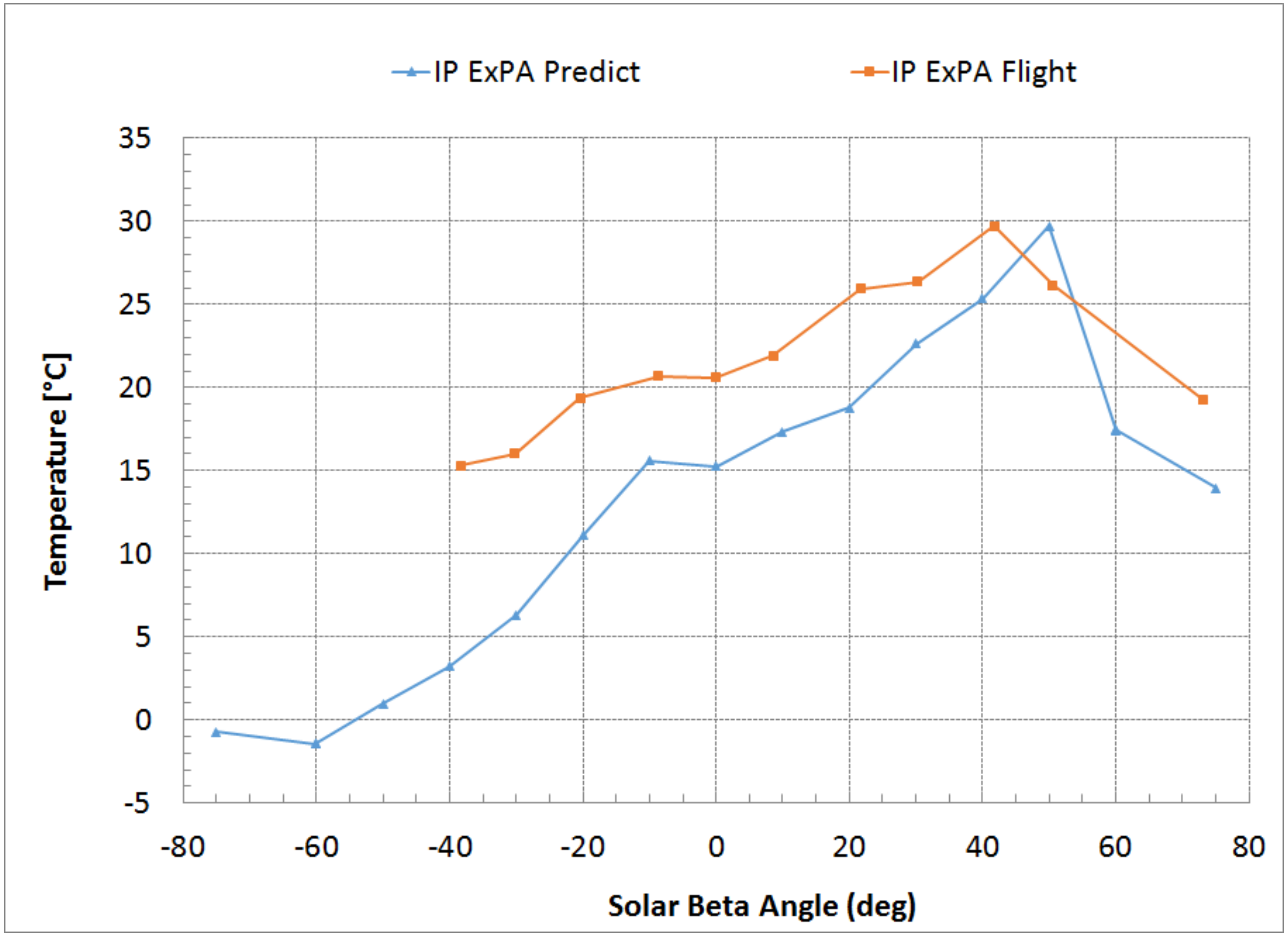
Limb-Scatter Event Correlation
(β = 41°)



Unpowered Correlation
(β = 45°)

ExPA Temp as a Function of Beta Angle

- ExPA under-prediction increases as beta becomes more negative



Conclusions

- Model quality very good: overall TVAC RMS error < 3°C
- Lessons learned: test definition and setup
  - Create test conditions focused on thermal behavior for correlation
  - Quartz lamps solar output can make correlation problematic
  - Characterizing new chamber equipment prior to payload testing is highly beneficial
  - Ensure TCs placed so basic assumptions can be verified
  - Make interfaces as flight like as possible
- Lessons learned: correlation
  - Best practice - proceed from simple to complex; correlate to hot and cold
  - Correlation to transients more reliable than to steady-state
  - Use of single model for flight and ground test scenarios greatly improves efficiency
  - RMS error very effective single measure of model quality
- Correlation, though complex, is worthwhile for flight predicts and finding systemic errors in the model

Acknowledgements

- Thank you to the SAGE III project personnel, and the Systems Integration and Test branch personnel, for support in accomplishing this TVAC testing.